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FINAL REPORT

ONR SBIR Contract N00014-91-C-0138

Fine Scale Measurements of Microwave Backscatter from the Ocean Surface

Submitted by

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1. INTRODUCTION

This report summarizes work performed under ONR contract number N00014-91-C-0138 "Fine Scale Measurements of Microwave Backscatter from the Ocean Surface". During this Phase II SBIR project we built a new-concept Focused Phased Array Imaging Radar (FOPAIR) system capable of producing very fine scale ($\approx$ 1m x 1m) radar cross-section and radial velocity images of the ocean surface. Phase II work began in July of 1991 and within 20 months we had completed preliminary tests of the entire FOPAIR system from a roof top site in Amherst, MA. On May 5, 1993 we brought the FOPAIR system to North Truro, MA, where we demonstrated the system's ability to image ocean surface waves at ranges up to 500 m. Following submission of this report, Quadrant will deliver FOPAIR to the University of Massachusetts Microwave Remote Sensing Laboratory. FOPAIR will be used initially to study scattering from breaking waves and will participate in the upcoming Marine Boundary Layer Accelerated Research Initiative (MBL-ARI).

1.1 System overview

The FOPAIR system consists of a 300 W peak-power chirped radar, a sequentially sampled 128 element receive array, a fast 12 bit data acquisition system, a 2 GByte disk drive, and all the necessary software to control the radar and process the data using a IBM-compatible PC. Range resolution of 1.5 m is achieved by using a pulse of 10 ns duration, while azimuthal resolution results from the antenna's large horizontal aperture. Based on a length of 6.9 m, the azimuthal beamwidth of the antenna is 5 milliradians – equivalent to 1 m azimuthal resolution at 200 m range. A 1:128 switching network sequentially connects the radar to the individual receiver elements of the array on a pulse-by-pulse basis allowing the complex voltage from all elements to be sampled in approximately 1 mS.

The capability to rapidly store the response of all 128 receiver elements makes FOPAIR a very versatile radar. In addition to providing two dimensional maps of radar cross-section, the data can be processed to yield images of radial velocity through use of a pulse pair algorithm or can be used to detect motion through MTI processing. In all of these cases the antenna pattern can be shaped in software to tradeoff azimuthal resolution against sidelobe level. Additionally, software calibration allows time delays and phase and amplitude errors inherent in the receiver array to be corrected through observations of a single corner reflector at a known location.

1.2 Chronology of the development of the FOPAIR system

The concept of employing a sequentially sampled phased array for generating high resolution images of the ocean surface was originally proposed by R. McIntosh in 1988. Such an array would form an image using processing techniques similar to that of a Synthetic Aperture Radar (SAR) but would form the image so rapidly that distortion due to ocean surface motion would be essentially eliminated. Following discussions with ONR personnel and other radar oceanographers, Quadrant Engineering proposed a Phase I SBIR to study to feasibility of building FOPAIR for use by the Navy for oceanographic research.

1.2.1 Phase I activities

Early in Phase I a strawman design was presented by the P.I. to a group of radar oceanographers at Wood's Hole Oceanographic Institute. Attendants included R. Beal (APL); G. Brown (VPI); F. Herr (ONR); R. Moore (KU); W. Plant (formerly of WHOI); R. McIntosh

(Quadrant Engineering and UMass) A. Ghandi (UMass) and the P.I. This meeting helped identify applications of such a system, and highlighted various technical problems associated with ocean surface imaging. Following this meeting, many of the final design parameters were selected, including operating frequency, antenna size, data acquisition and data storage techniques. This preliminary design was then submitted to ONR for Phase II approval.

1.2.2 Phase II activities

The goal of the Phase II SBIR was to build a complete FOPAIR system, including a sequentially sampled array, short pulse radar, data acquisition system, data storage system, and processing and display software. The phase I design was refined during the first three months of Phase II, with only two major design changes: 1) to increase the transmitter power from 20 to 200 W and 2) to use a separate transmitter antenna. The added power assured that there would be sufficient signal-to-noise ratio to sample the ocean surface to distances up to 500 m while the separate transmit antenna improved the sidelobe performance of the array.

The Linear Tapered Slot Antenna (LTSA) elements selected for use in the 128 element array required a significant development effort, which was supervised by a consultant to Quadrant, Dr. David Pozar of the University of Massachusetts Antenna Laboratory. After a six month design cycle a sub-array of eight LTSA elements was tested and was found to perform well. To simplify construction and assembly, the array was designed in eight modules of sixteen elements each. Each module was 0.85 m long, for a total array length of 6.9 m. These modules included the 1:128 switching network necessary to steer the receiver to the proper LTSA element.

During the first year of Phase II Quadrant also built the radar subsystem and the digital system to control the radar and antenna switching network. Other major activities during the first year included acquiring the two major data acquisition subsystems, the Analytek sampler and the Storage Concepts fast data cache. These two systems were integrated by engineers at Analytek and delivered in June, 1992.

Before system integration and field testing could begin a significant effort was put towards writing the software necessary to control the radar and data system, to process data, to display data, and to calibrate the radar. This software was written to run from a windows environment on a IBM-compatible PC. Having this software available before system integration greatly simplified radar debugging and data visualization.

After 18 months we had taken delivery of all major radar and data acquisition components and began system integration in January 1993. The first test of FOPAIR was made with a single sixteen element module, from which we were able to produce focused images of a corner reflector utilizing a simple brute force focusing algorithm. This routine provided perfectly focused images but was computationally intensive, requiring 30 s on a 486 PC to process a single focused image of 64 x 64 pixels. Because the radar generated up to 150 such images per second this algorithm was deemed too slow for field applications. This problem was eventually solved by implementing a Fast Fourier Transform (FFT) to focus the beam within a limited depth of field. While this algorithm leads to minor focusing errors it is 4[illegible] times faster to execute than the brute force method, making it practical for field use.

The first test of the full system was made in April, 1993, from the top of a 25 m high building. These tests indicated that the array calibration was stable with time and also showed that sufficient isolation could be achieved between the transmit and receive antennas to allow chirp mode operation at short ranges.

The first ocean imaging test of FOPAIR was made on May 5, 1993 from the Head of the Meadow beach in North Truro, MA, on Cape Cod. Witnessing the test were D. Trizna from ONR and K. Melville from Scripps Institute of Oceanography. During this one day test we successfully imaged 50-60 m long swells to ranges of 500 m with excellent results. In addition, we collected nearly 2 GBytes of raw data, which included several 5 minute records of ocean swells and breaking waves. Some of this data is presented at the end of this report.

In the following chapter we provide a description of the major subsystems of the radar. In chapter three we describe the Windows-based software for controlling the radar and processing the data. The fourth chapter discusses the operating modes of the radar, including short pulse mode, chirp mode and pulse pair mode. The fifth chapter describes the field tests of FOPAIR, and presents ocean surface images of both radar intensity and velocity.

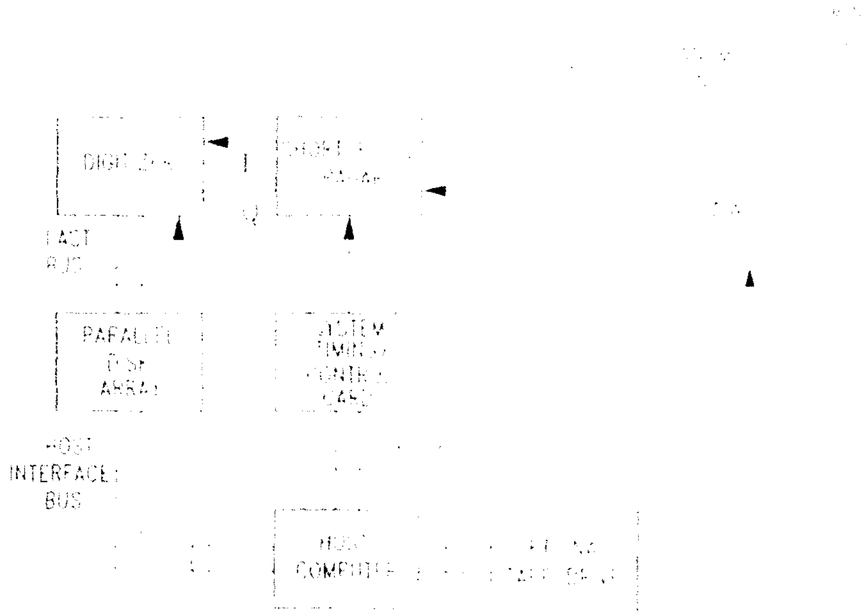

Figure 1: FOPAIR system block diagram

2. DESCRIPTION OF SUBSYSTEMS

The major subsystems and components of the FOPAIR system are shown in Figure 1 System parameters are listed in Table 1. FOPAIR operates at 10.0 GHz (X-Band) and includes a pyramidal horn transmitting antenna (illuminator), a 128-element receiving array, a switching network to sequentially select receiving antenna elements, a short-pulse/pulse-compression radar system, a fast data acquisition system with fast disk storage, and a control/display computer console. The subsystems are described in detail below.

parameter	value
General:	
operating frequency	10.0 GHz
master clock frequency	20.0 MHz
Transmitter:	
output power	300 W
short pulse length	8-100 ns
chirp pulse length (compressed)	10 ns
chirp pulse length (expanded)	2000 ns
chirp gain	21 dB
PRF	200 KHz, max
Receiver:	
intermediate frequency	400 MHz
noise figure	8-11 dB
bandwidth	200 MHz
Digitizer:	
number of bits	12
real dynamic range	45 dB
number of channels	2
record length per channel	8192
number of samples per antenna	64
sample rates	100, 200 or 400 MHz
full array sampling rate	150 Hz

Table 1: System Specifications

2.1 Radar transmitter/receiver

The radar subsystem, shown in Figure 2, can operate either as a short-pulse radar or as a pulse-compression radar. For short ranges, the expander/compressor circuitry may be optionally switched out of the circuit. Pulse widths between 8 and 100 ns may be selected, resulting in range resolutions between 1.2 and 15 m. Computer simulations indicate that the system has sufficient signal-to-noise ratio (SNR) to image the ocean surface to 100 meter range in short-pulse mode. Beyond this, the expander/compressor circuitry will be used, increasing the SNR by approximately 21 dB, and the maximum range to approximately 500 m. Using the expander/compresser network the range resolution is approximately 1.5 meters.

The final amplifier in the transmitter chain is a Varian VZX6983G5 travelling wave tube amplifier (TWTA) capable of 300 W peak power output, CW. This amplifier has approximately 44 dB gain and requires 15 mW drive to provide a saturated output. The amplifier draws approximately 20 A at 110 VAC, so care must be taken to provide a separate circuit to run the TWTA to avoid tripping the AC circuit breaker.

2.2 Antenna array

The receiving antenna assembly consists of 128 individual Linear Tapered Slot Antenna (LTSA) elements in eight modules, a frame supporting these modules, the individual coaxial feed lines for all elements, and the first two tiers of the switching network. The array linear dimension is approximately 6.9 m. This dimension was determined by maximizing azimuthal resolution subject to grating lobe suppression considerations and inter-element mutual coupling. The antenna elements are packaged in modules of 16 elements, each with

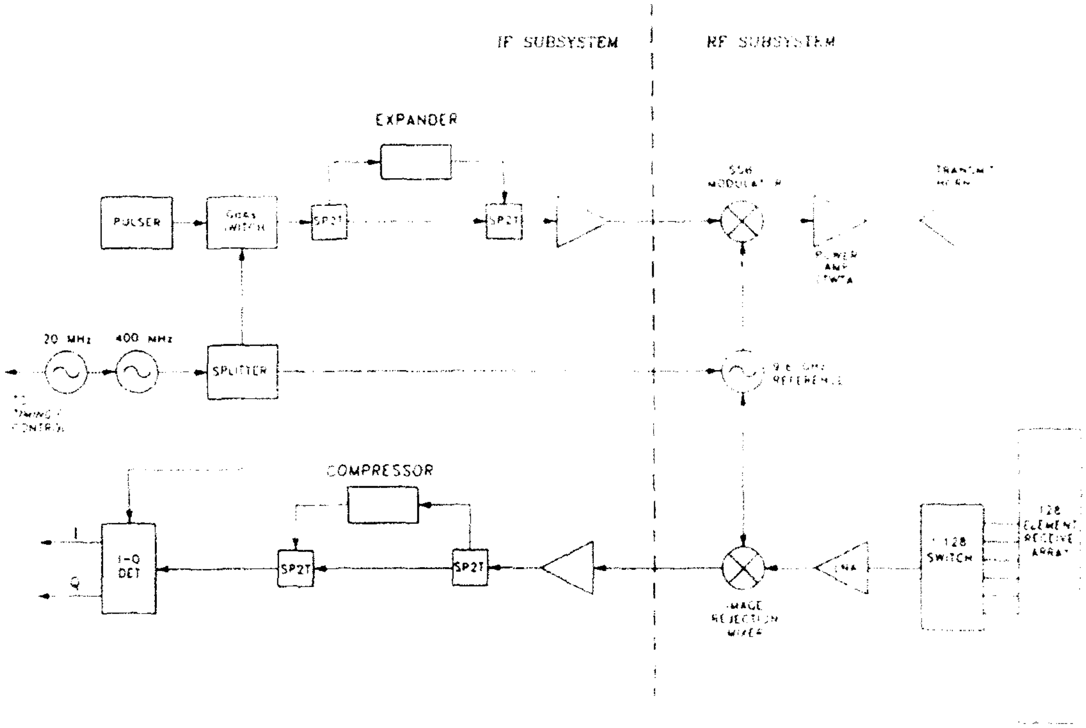

Figure 2: Radar transmitter/receiver block diagram

their associated coaxial cabling and switching hardware. These eight modules are deployed end-to-end along a supporting framework to form the full array. A separate waveguide pyramidal horn antenna is employed for the transmitter for several reasons: 1) The peak transmit power can be much higher than the 10 W peak power possible with the receive array switching network 2) the transmit antenna pattern may be controlled independently of the receive antenna pattern to allow better suppression of grating lobes 3) sufficient isolation can be achieved to allow use of chirp mode for ranges below 300 m (the nominal length of the stretched chirp pulse). By mounting the transmit horn at one end of the receiver array we have achieved greater than 100 dB isolation between the transmitter and receiver. This allows us to operate in chirp mode at any range without having to worry about excessive range sidelobes associated with antenna to antenna coupling.

Array and element specifications are given in Table 2. The field of view of the antenna as determined from the -6 dB contour of the two-way antenna pattern is 20° in azimuth and 17° in elevation. The 20° azimuthal field of view results in a 105 m wide azimuthal swath at a range of 300 m. Assuming an array height of 10 m above the surface, the 17° elevation field of view allows the antenna to illuminate all ranges from 34 m to infinity without having to adjust the antenna in elevation.

2.3 Receiver switching network

The switching network consists of a tree of SP2T and SP8T switches. The first level of switches (consisting of 16 SP8T switches) are mounted directly behind the LTSA elements, with short runs (8" or less) of .085" diameter semi-rigid cables (SSMA male to SMA male) connecting the elements to the switch. The second tier of switches (consisting of two SP8T

FOPAIR antenna specifications	
receiver antenna:	
receive element	Linear Tapered Slot
number of elements	128
array length	6.86 m
element spacing	5.4 cm (1.8 λ)
H-Plane 3 dB beamwidth	25°
E-Plane 3 dB beamwidth	19°
gain	15 dB
focused beamwidth	0.25°
azimuth resolution	1 m at 200m range
transmit antenna:	
antenna type	waveguide pyramidal horn
H-Plane 3 dB beamwidth	16°
E-Plane 3 dB beamwidth	16°
gain	21 dB
two-way antenna properties	
azimuthal field of view (-6 dB)	20°
elevation field of view (-6 dB)	17°
tx-rx isolation	>100 dB

Table 2: Antenna Specifications

switches) are mounted in the third and seventh antenna module. These are connected to the first tier using .141" diameter semi-rigid cables (SMA male to SMA male) of up to six foot lengths. The switches have a maximum insertion loss of 1.9 dB each; the .085 dia. cable has a loss of .65 dB/ft. and the .141 dia. cable has a loss of .39 dB/ft. Given these values, the total insertion loss for the network is expected to be a minimum of 5.5 dB and a maximum insertion loss of 8 dB. The second tier switches are followed by low noise amplifiers with 2.0 dB noise figure. Including dielectric and conductor losses in the LTSA antenna elements, the overall noise figure (the sum of all losses before the LNA + the LNA noise figure) is approximately 8-11 dB, depending on the length of cable associated with a particular LTSA element. The final SP2T switch in the network is incorporated into the radar receiver's RF front-end. A pair of low-loss flexible coaxial cables are used to connect the radar to the antenna array subsystem.

2.4 Data acquisition subsystem

A two channel, 12-bit data acquisition system, the Analytek System 2000, was purchased from Analytek, Inc., now a fully owned subsidiary of Tektronix. This system is capable of very high sampling rates (up to 2 GBytes/s), with a video bandwidth of approximately 350 MHz. Each channel of the sampler stores up to 8192 analog samples in a single acquisition burst, which are converted by a 12-bit A/D converter and dumped to either a video display or the fast data cache. The Analytek data system can fill the analog buffer and convert the data about 150 times a second, for a net througnput rate of approximately 5 MBytes/s.

2.5 Fast data cache

A Storage Concepts Concept 51 fast data cache was purchased to store the data output from the Analytek sampler. The data cache consists of an array of three 780 MByte disk drives, for a total data volume of 2 GBytes. The data cache can store data at approximately 5.8 MBytes per second, sufficient to handle the full rate of the Analytek sampler. A custom VME interface card was developed by Analytek to handle the data transfer between the data cache and the sampler. Data transfer between the PC and the data cache are routed by a custom bus developed by Storage Concepts. Data can be uploaded from the data cache to the PC at a rate of approximately 250 KBytes/s. For long experiments the data may be offloaded to 8 mm tape at an overall rate of approximately 125 KBytes/s.

3. Control, acquisition and processing software

All of the data acquisition and control software for the FOPAIR system was developed under Microsoft Windows (version 3.1) using "Borland C++ and Application Frameworks" (version 3.1). This development system provides a convenient way to organize large software projects containing many modules. It also includes a package called "ObjectWindows for C++" which provides a template for creating object-oriented Windows applications. The software may be divided into two categories: User Interface and Device Drivers. The User Interface is written in C++ and uses many of the features of the ObjectWindows package, while the Device Drivers are written in C and are intended to be reasonably compiler independent. This section will describe the major features of each software category.

3.1 User interface

The main user interface to the FOPAIR system is a Windows application called ACQUIRE. This application consists of a single control panel that the user fills in to configure an acquisition cycle. Once all the parameters have been specified, the user clicks on the "Setup" button in the control panel. The program then communicates the desired acquisition parameters to the various hardware devices (radar controller, sampler, disk array, etc.), and prepares the system for an acquisition. Once the system is ready, the user is prompted to initiate an acquisition. This is accomplished by clicking on the "Sample" button in the control panel. Details of the acquisition parameters and the specific actions taken during each phase of the acquisition are given in the FOPAIR users manual, available upon request from Quadrant Engineering.

3.1.1 Device drivers

Control of the FOPAIR system hardware is achieved through several device interfaces. Each device in the control and data acquisition system has an interface card that resides on the PC bus. The devices and their interfaces are detailed in the following subsections.

Radar and Array Control. The radar is controlled by a custom designed control card and by a D/A converter card used for pulse width control. The custom control card is built around an Industrial Computer Model PB-750AT prototyping card: a full size AT-style card including PC Bus interface logic and power and ground busses. A large prototyping area is occupied by 3 Xilinx FPGAs (programmable gate arrays) that contain our application specific control circuitry. The D/A converter card is an Industrial Computer Model AOB2P. It provides a 0-10V (static) control signal to the pulser in the radar transmitter. Both devices are controlled by writing the desired settings to memory mapped registers on the cards. The program files "radriver.c" and "radriver.h" contain all the necessary control software for these two cards.

Analytek System 2000 Sampler. The Analytek is controlled through a National Instruments IEEE-488 (GPIB) interface card. This card comes with both DOS and Windows device drivers which are memory resident in the PC. Driver routines specific to our application which access the vendor supplied device drivers are located in "andriver.c" and "andriver.h"

Storage Concepts Concept-510 Disk Array. The Concept-510 is controlled by a proprietary PC Host-Interface card, and a DOS-compatible handler library called "c51hand.lib".

The handler library provided by Storage Concepts provides only a very low level interface. A rudimentary file control system has been developed to handle simple file I/O operations which is adequate for the needs of the FOPAIR system. These file control routines are located in "c51file.c" and "c51io.c" Although the vendor supplied device driver is not strictly Windows compatible, it does function properly within a DOS-environment window opened under Windows.

3.2 Data processing

3.2.1 Quick-look processing

A Windows application called QLOOK was written for viewing raw and processed data files. This program is used to view data graphically on a frame-by-frame basis. It includes a number of plot style preferences and can generate hardcopy output in PostScript or HPGL format. QLOOK requires that the data to be viewed is located on the PC's hard disk. By double clicking on its icon, a window is opened with pull-down menus and three slide bar controls. Once opened, the user can specify which parameters to view in a plot window. Separate pull-down menus specify the "x-variable" and the "y-variable" to plot. Y-variables include 1) I-channel, 2) Q-channel, 3) magnitude, 4) phase, and 5) intensity (relative power in dB). These may be plotted (1) vs. range gate for 1) a given element, 2) vs. element for a given range gate, 3) vs. azimuth (for focused results), or 4) vs. sampling card index (for raw data dumps). Three slide bars allow the user to rapidly scan data. One slider controls which frame to view (a frame is one complete acquisition cycle from the full array), another which array element, and the other which range gate.

QLOOK also provides a quick way to phase-calibrate the array. By viewing the magnitude or intensity response of a hard-target (such as a corner reflector) vs. element number, one can easily locate the range gate containing the peak response. Under the "Focusing" menu, an option to calibrate on a target can be selected. This generates a file of calibration coefficients for each array element. The calibration can then be included in the data viewing by opening it under the "File" menu. The details of calibration are given in section 3.3.

3.2.2 Image focusing algorithm

A DOS and Unix compatible program for generating focused complex imagery from the raw data has been written. It is called QIMAGE and is designed for batch processing of data. The user edits an input parameter file called "qimage.inp" specifying the details of the desired focusing. A binary file of focused images is created which may be subsequently viewed and post-processed using a 2-D capable data analysis and display package such as IDL. The details of the focusing algorithm are given below.

Once phase and amplitude calibration have been applied to the data, focusing can be performed. A conventional phased array antenna viewing a target in the far field can employ a Fourier transform to convert the measured field signal across the array into an azimuthal scan. An N-point Fourier transform applied to the responses of N array elements generates N simultaneous orthogonal beams. These beams span the entire "visible space" of the array and thus provide a complete azimuthal scan of the array's field of view. FOPAIR suffers the complication that the target of interest is always in the near field (or Fresnel region) of the array, which prevents the direct application of the Fourier transform. In this case, diffraction limited focusing can be viewed as requiring two steps. First, a linear phase taper applied across the array steers the array's main beam in a given direction. Then, a quadratic phase taper "pulls" the focal point of the array in from infinity to the finite range of interest. This forces targets at the range of interest to appear like far field targets. In practice, it is most efficient to perform the second step first. That is, once the targets at a given range are made to appear like far-field targets, conventional FFT processing can be used to perform an azimuthal scan.

The image focusing algorithm processes the data on a range gate by range gate basis. For each range gate, the complex samples from all array elements are loaded into a vector, multiplied by both a range focusing correction and an amplitude taper, and Fourier Transformed. The resultant vector is a focused azimuthal scan of the visible space of the array ($\pm 16°$). Because of grating lobe rejection issues, we are only interested in the central half of the visible space, corresponding to $\pm$ 8°, so half of the focused samples are usually discarded.

Depth of focus. The "depth of focus" of a focused array is the extent of ranges over which a single range-focusing correction yields adequate focused results. It is analogous to a "beamwidth in range." For certain viewing geometries, several different range focusing corrections need to be applied in forming an image - one for each depth of focus. A conservative measure of the depth of focus, δ_R, is:

$$\delta_R = 2\lambda \frac{R^2}{L_{array}^2} \tag{1}$$

where λ is the radar wavelength (.03 m), R is the range to the scatterer, and L_{array} is the length of the array (6.86 m). The focusing algorithm calculates this measure and generates as many range focusing corrections as are necessary to span the depth of the image.

Range bin migration. Under certain viewing geometries, a phenomenon called range bin migration can seriously affect the ability of this algorithm to focus. When the difference in range from a scatterer at a given location to either end of the array exceeds the range resolution of the radar, the data corresponding to that scatterer's response "slips" from one range gate to the next. As a result, a scan of a single range gate's data across the array will not include all the energy from that scatterer, and so a Fourier transform of that data will not yield "full" focusing on that scatterer. This problem is most severe for scatterers at short ranges and large azimuth angles (relative to broadside) when high range resolution and a large aperture are used. For most practical cases, this effect can be minimized by suitable choice of data acquisition and processing parameters.

3.3 Calibration

3.3.1 Amplitude and phase correction

In order to focus the array properly, it is necessary to know the phase delay and loss associated with each of the 128 elements in the array. There are several factors that can affect these parameters including differences in cable length, antenna losses, connector loss, mismatches along the transmission path, and so on. These effects can be lumped together into a single correction for phase and amplitude, or, more succinctly, a single complex multiplication.

Calibration using a single corner reflector. Calibration is most easily achieved by observing a strongly reflecting point target, such as a corner reflector, at a known range located on a line perpendicular to and centered on the array. The corner reflector should be placed sufficiently far away to illuminate the array nearly uniformly in amplitude. This can be achieved for ranges that meet the following criteria:

$$R \geq \frac{2dL_{array}}{\lambda} \tag{2}$$

Where d is width of the corner reflector in the horizontal plane. For a corner reflector .3 m in width, ranges greater than 137 m should be adequate.

The backscattered field from the corner reflector will be nearly uniform in amplitude, and will have a quadratic phase variation across the array, due to the spherical nature of the phase-front associated with scattering from a point target. Given the relative geometry of the calibrating point source and the array, one can calculate what the relative phase variation of the signal should be as a function of array element position. For a point target located broadside to the array, the theoretical phase variation is:

$$\phi_{ideal}(x) = \frac{\pi x^2}{\lambda R} \tag{3}$$

so the ideal complex samples would be:

$$v_{ideal}(x) = A(cos(\phi_{ideal}(x)) + j * sin(\phi_{ideal}(x))) \tag{4}$$

where A is a scaling factor described below. The calibration coefficient is simply

$$calib(x) = \frac{v_{ideal}(x)}{v_{measured}(x)} \tag{5}$$

where

$$v_{measured}(x) = I_{channel}(x) + j * Q_{channel}(x) \tag{6}$$

The calibration corrects the phase of the signal at each element and also *enforces uniform* illumination across the array. The magnitude of $v_{ideal}(x)$ is scaled to the average magnitude as measured across the array so that calibration coefficient magnitudes are of the order of 1. This calibration works best when the calibrating point source provides a high signal-to clutter ratio.

4. Operating modes

The radar may be operated as a conventional short pulse radar or as a chirp radar. The short pulse mode has the advantage of variable pulse widths (8-100 ns) and has no range sidelobes. Chirp mode has a fixed compressed pulse width of 10 ns, and has near-in range sidelobes approximately 30 dB below the peak response. The use of these two modes is described in more detail below.

4.1 Pulse mode operation

Pulse mode should be used whenever the scattered signal is strong enough to provide adequate signal-to-noise ratio (SNR). For imaging applications, an average SNR of 10 dB or greater should be adequate. For measurements of scattered power statistics an average SNR of 22 dB will assure that 99.5% of the data will be above the average noise level. The shortest pulse available is approximately 8 ns long, yielding a range resolution of 1.2 m. By using longer pulses the SNR will improve as the ratio of pulse lengths, but will result in loss of spatial resolution.

When operating with the shortest available pulse (8 ns) the digitizer may be used at a sampling rate of 100, 200 or 400 MSamples per second, corresponding to sampling intervals of 10, 5 and 2.5 ns. The fastest rate (2.5 ns) provides a factor of three oversampling in time which is useful when trying to locate the peak response of a hard target, such as a corner reflector. For clutter imaging, it is probably adequate to sample at the 10 ns spacing, which will yield the greatest range coverage (64 gates * 10 ns = 640 ns, equivalent to 96 m in range), and will provide 1.5 m range resolution.

Range coverage may be doubled or quadrupled by sampling only 1/2 or 1/4 of the array.

This has the effect of doubling or quadrupling the azimuth pixel width, but may be a good tradeoff for observations below 200 m range. For example, at a range of 100 m equal azimuthal and range resolution (approximately 1.2 m x 1.2 m) may be achieved by sampling only half the array. This would allow 128 range gates to be sampled which is equivalent to 192 m range coverage at 100 MSamples per second sample rate. Sampling half the array may also be desirable when operating in pulse-pair mode as described in section 4.3.

4.2 Chirp mode operation

When observing weakly scattering scenes, such as the ocean surface under low wind conditions, or when making measurements at long ranges, an additional 21 dB gain in SNR may be achieved by operating in chirp mode. Chirped mode in activated by directing a short, high bandwidth pulse through a dispersive delay line which generates an expanded pulse of 2000 ns duration. Upon reception, this expanded pulse is passed through another dispersive delay line which reverses the expansion process, resulting in a compressed pulse of 10 ns duration. The ideal response of the expander/compressor pair is shown in Figure 3, showing near-in range sidelobes at approximately -30 dB with respect to the peak response. Far-out range sidelobes are suppressed by approximately 60 dB.

Range sidelobes associated with leakage between the transmitter horn and receive array could potentially mask weak returns from the scene under observation. To avoid this problem, a minimum isolation of 100 dB is required between the transmit and receive antennas. By mounting the transmit horn on one extreme end of the receive array it is possible to achieve greater than 100 dB isolation.

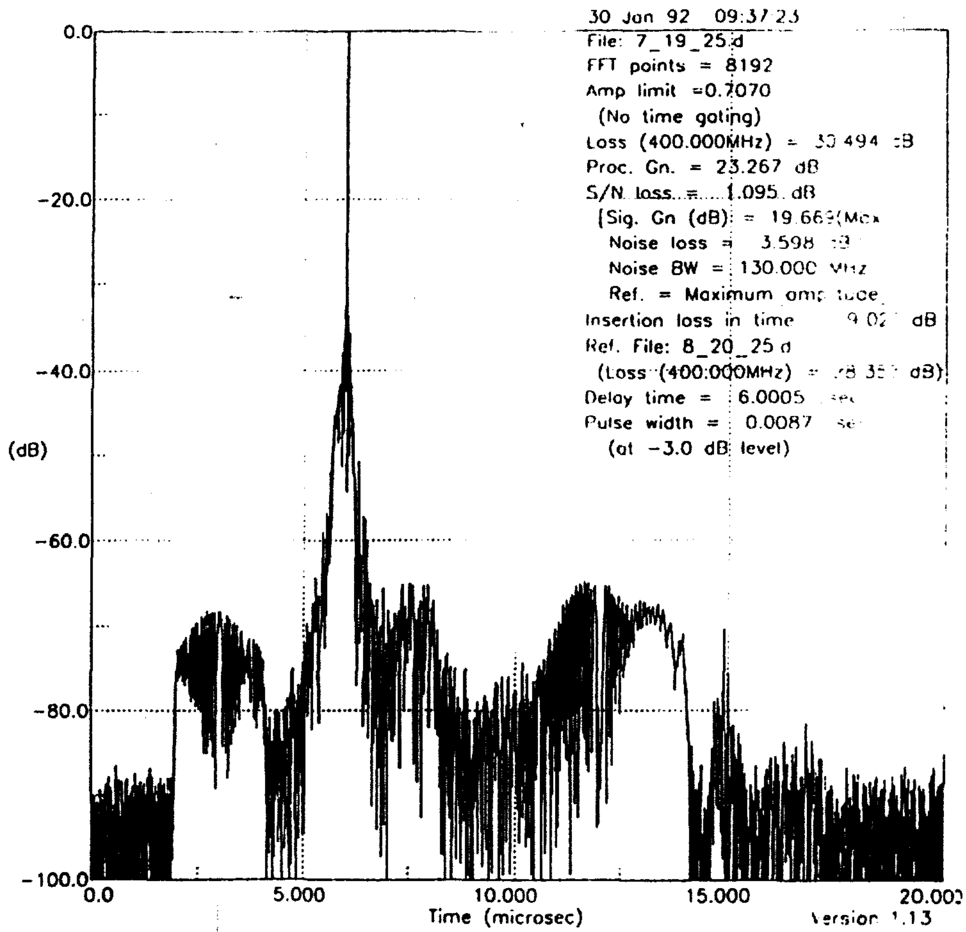

Figure 3: Time domain pulse at output of Sawtek compressor

4.3 Pulse-pair mode

Measurement of the radial velocity of each pixel within a focused image can be achieved through use of a pulse-pair algorithm. This algorithm works by sampling the scene with two pulses spaced closer than the decorrelation time of the scattered signal. The maximum unambiguous Doppler velocity that can be sampled is given by:

$$v_{max} = \frac{\lambda}{4T_{sample}} \quad (7)$$

where $\lambda = .03m$ and T_{sample} is the time between successive images ($T_{sample} = 1/f_r$ where f_r is the frame rate).

The pulse pair algorithm can be used with the standard data acquisition mode, but the normal frame rate of 150 frames per second limits v_{max} to 1.1 m/s. However, a special pulse-pair mode is available that can sample half the array twice in the time normally allotted for sampling the full array. At a pulse repetition rate of 100 KHz T_{sample} =1.28 ms, thus, v_{max} is improved to 5.8 m/s. Sampling half the array results in a 50% reduction in azimuthal resolution, but should still be adequate for most applications.

5. FIELD TESTS OF FOPAIR

5.1 Roof top evaluation

In April, 1993 we brought FOPAIR to the top of a 25 m high building on the campus of the University of Massachusetts. This building overlooked a nearly flat playing field, which was between 40 and 160 m from the radar.

To calibrate the antenna, we placed a triangular trihedral corner reflector (radar cross section = 185 m^2) at a range of approximately 145 m. The amplitude response of the array is shown in Figure 4, showing $\pm$ 6 dB variability across the array before calibration. The first and last elements are distorted due to asymmetric loading by adjacent elements, and are therefore discarded when processing the focused beam. The focused array pattern is shown in Figure 5, where a 30 dB Chebyshev amplitude taper was employed. This pattern was formed by observing a corner reflector at a range of 142.5 m and scanning the array in azimuth by applying a varying linear phase correction. The calibration file used in generating this pattern was based on another corner reflector measurement made seven days earlier. The peak sidelobe level of -26 dB reflects combined amplitude and phase errors due to system drift, system thermal noise and quantization error as well as slight changes in the distribution of clutter.

An image of the corner reflector and the playing field is shown in Figure 6. In addition to the corner reflector located at 143 m in range (red spot), a plastic fence with metal posts is clearly visible at a range of 154 m, and trees are visible at a range of 165 m.

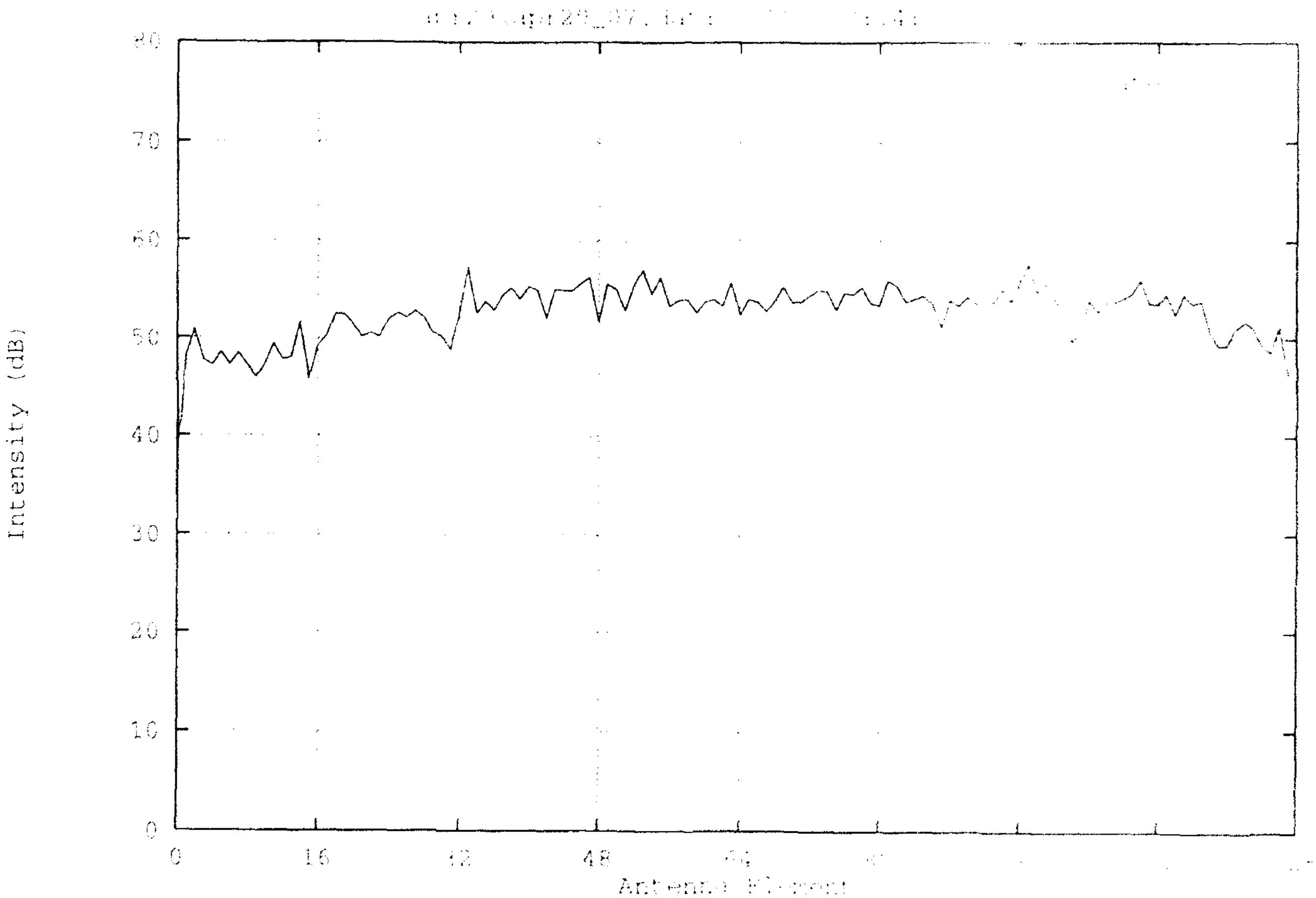

Figure 4: Uncalibrated amplitude response of FOPAIR array vs. element number

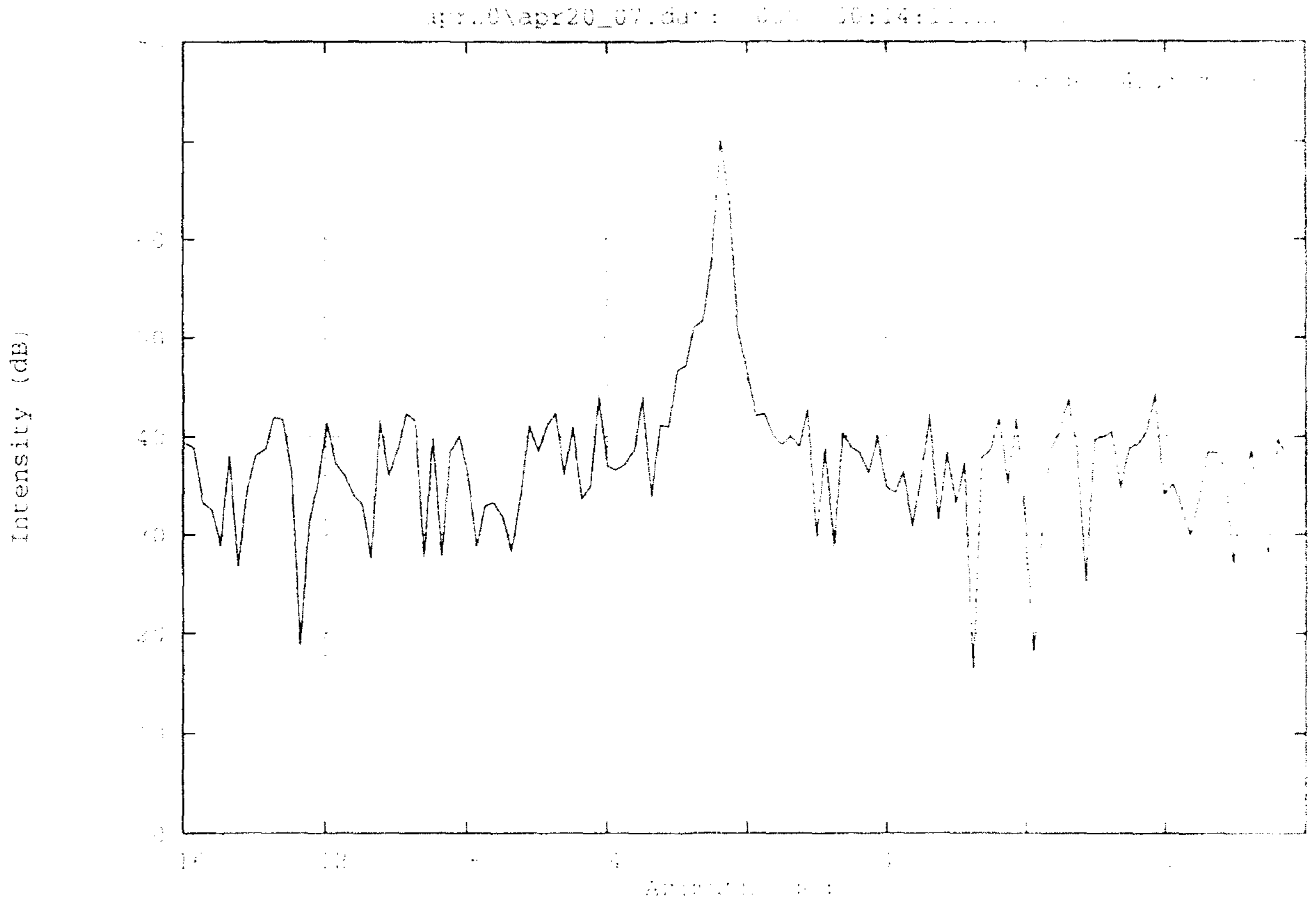

Figure 5: Azimuthal response of array to a single point target

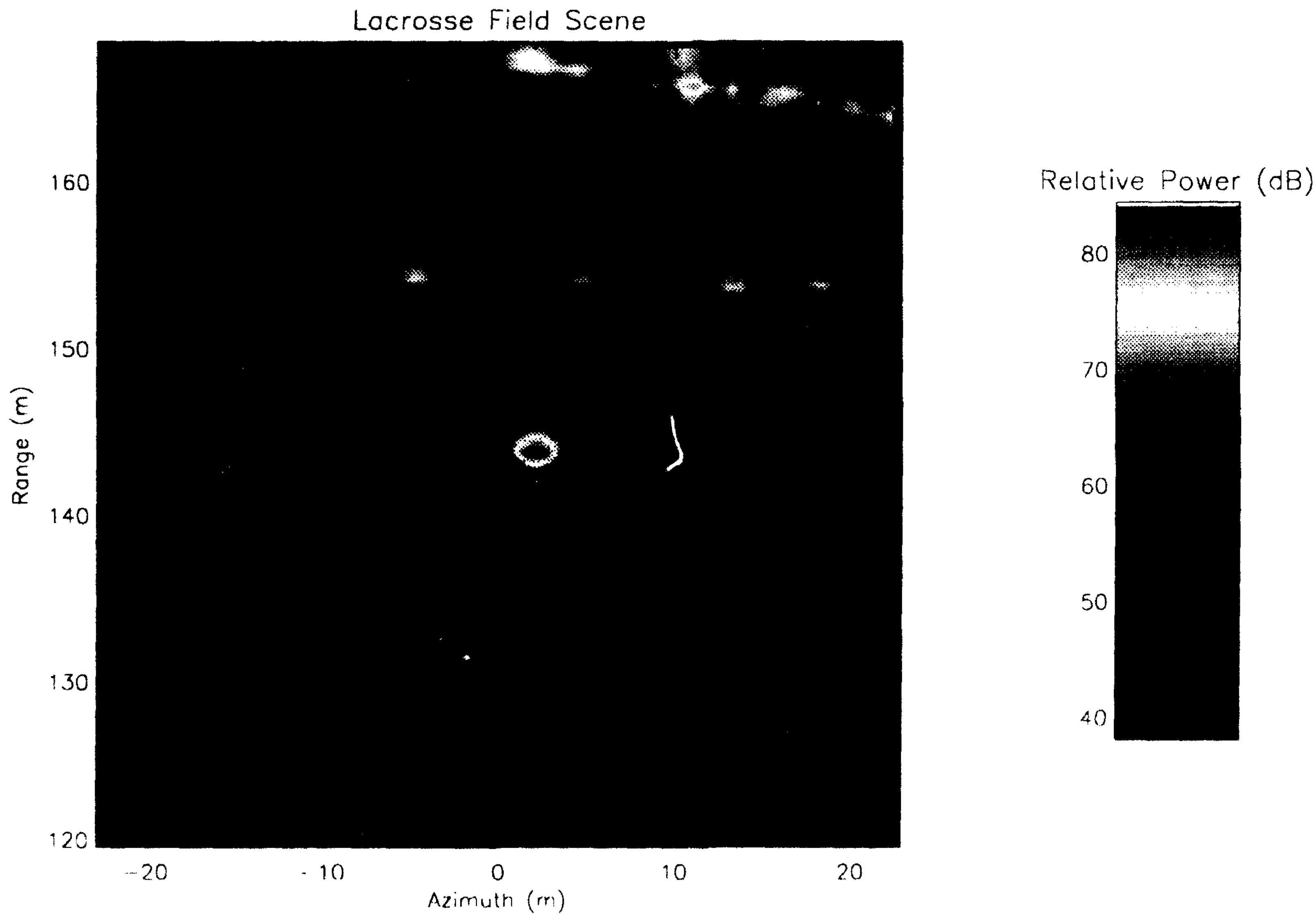

Figure 6: Backscatter intensity image of playing field, with corner reflector, fence, and trees.

5.2 Ocean surface imaging experiment, N. Truro, MA

The first ocean surface imaging test of the FOPAIR system was conducted from Head of the Meadow Beach in North Truro, MA on the eastern shore of Cape Cod on May 5, 1993. The radar was set up by a crew of four in less than two hours. All equipment was powered by a 5 kW generator with two 20 A circuits. The radar was situated approximately 30 m from the shore line and was about 5-8 m above the ocean surface. The antenna was calibrated by placing a large corner reflector on the beach about 230 m to the north of the radar site.

The first images of the surface were made around noon, about 3 hours past high tide. The wind was blowing steadily off shore, therefore, no wind driven gravity waves were present. However, there were well defined 1-2 m high swells present throughout the day. Figure 7 is a backscatter intensity image made at a range of 300-400 m. This image was despeckled by averaging together 20 frames, gathered at a frame rate of 150 frames per second. During the averaging time (.13 s) the wave crest moved less than 2 m, (less than two range gates) so very little spatial smearing has occurred in the image. Similar images with slightly reduced signal-to-noise ratio were measured at ranges up to 500 m.

The data gathered for Figure 7 may also be processed to produce images of radial velocity using the pulse pair algorithm described above. Figure 8 shows that negative velocities (points moving away from shore, colored blue) are located slightly in front of the backscatter intensity peak of the wave crest.

By late afternoon the tide had receded far enough so that significant wave breaking was occurring at well beyond 400 m range. Figure 9 shows a very strong "sea spike", probably due to specular scatter off the wave front. In addition, the non-breaking part of the wave is clearly visible along the same diagonal to the upper left and lower right of the sea spike region. The horizontal streaks surrounding the sea spike are due to azimuthal sidelobes near the -30 dB level. The vertical streaks in front of the sea spike are due to range sidelobes, and roll off into the noise after several range gates. The vertical streaks behind the sea spike are caused by use of an AC coupled amplifier after the I/Q detector. We have subsequently replaced these amplifiers with true DC coupled pulse amplifiers that should alleviate this problem.

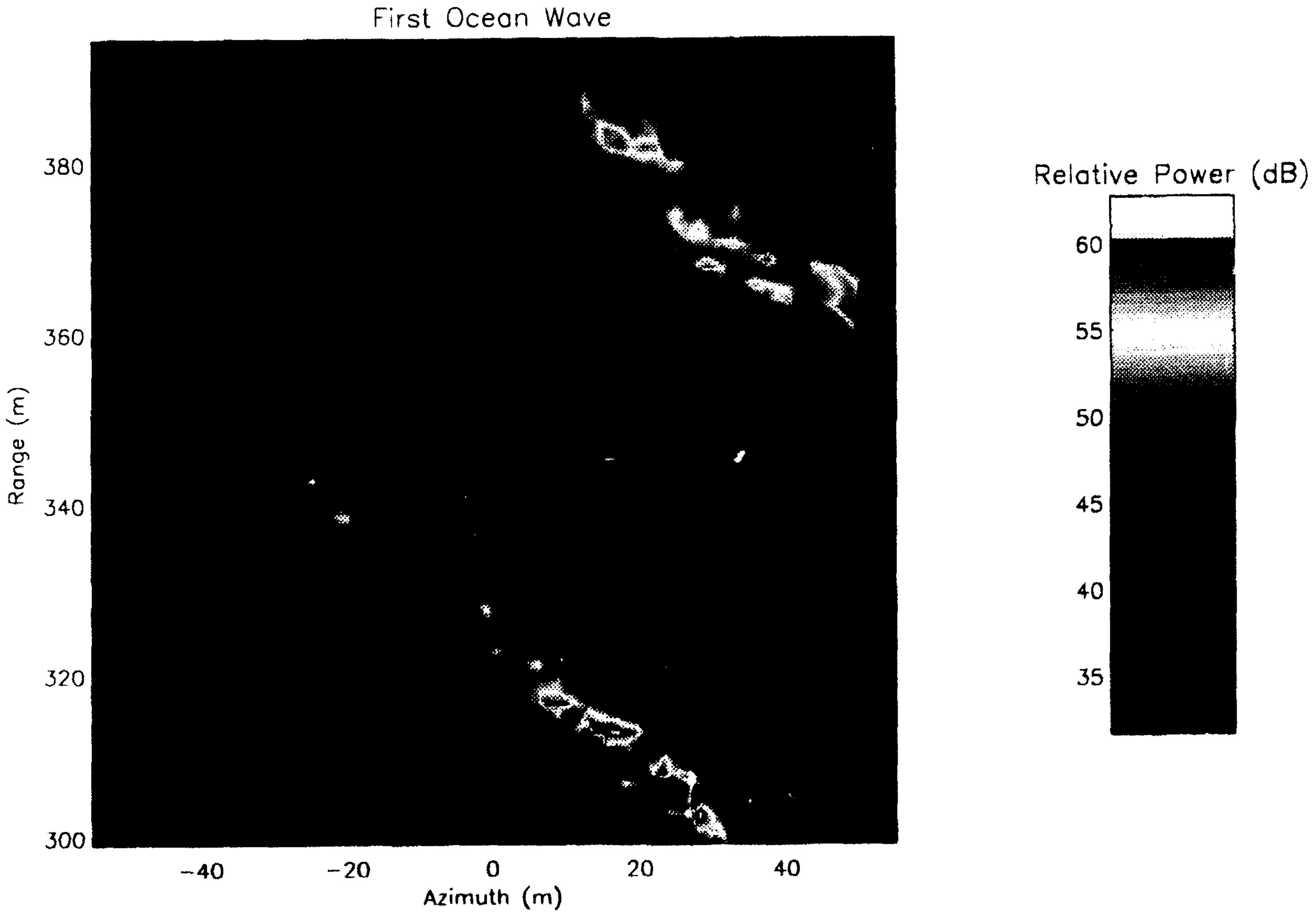

Figure 7: Backscatter intensity of ocean surface showing swells of 60 m wavelength.

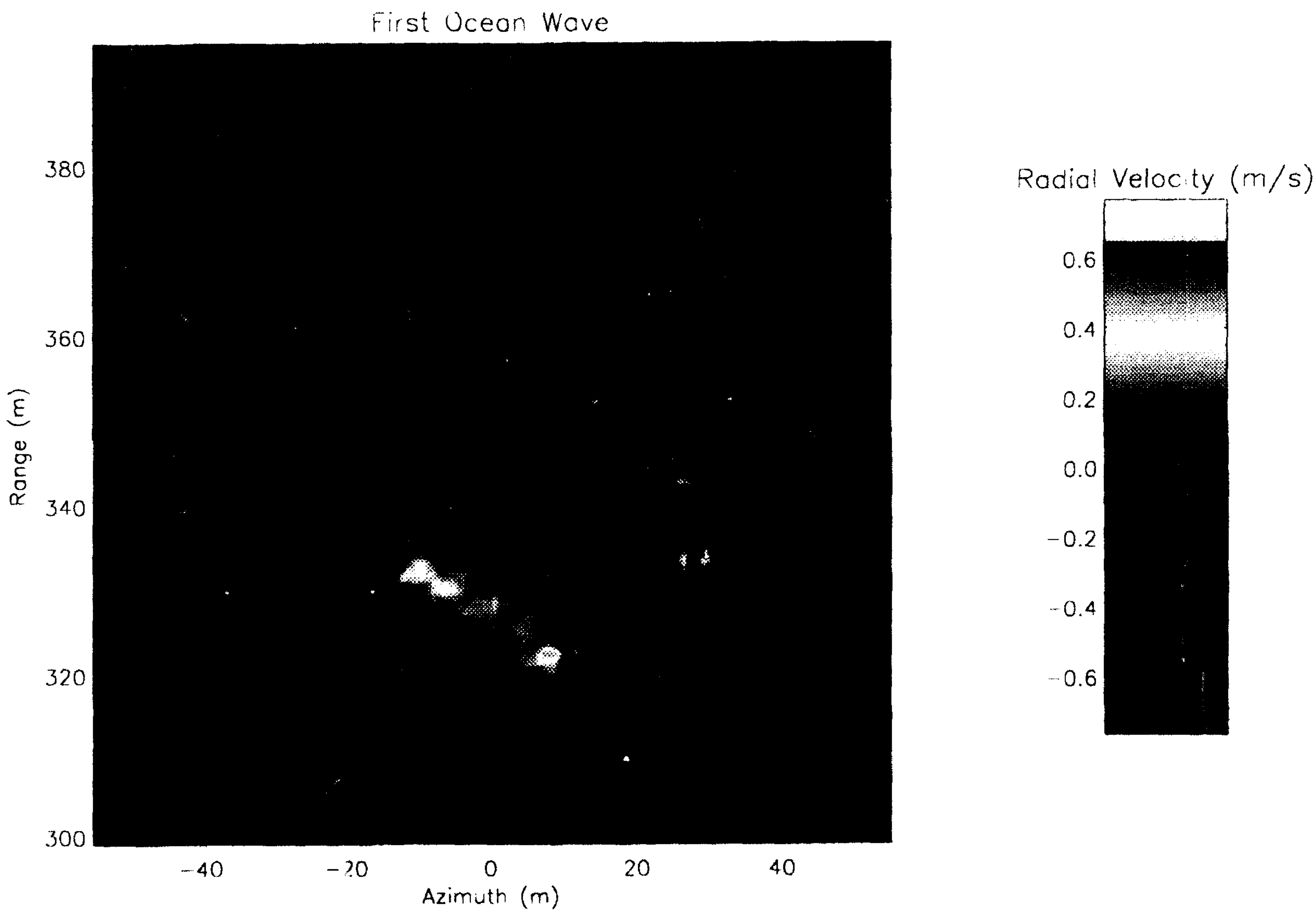

Figure 8: Doppler image of 1 to 2 m high swells. Negative velocities are moving away from shore.

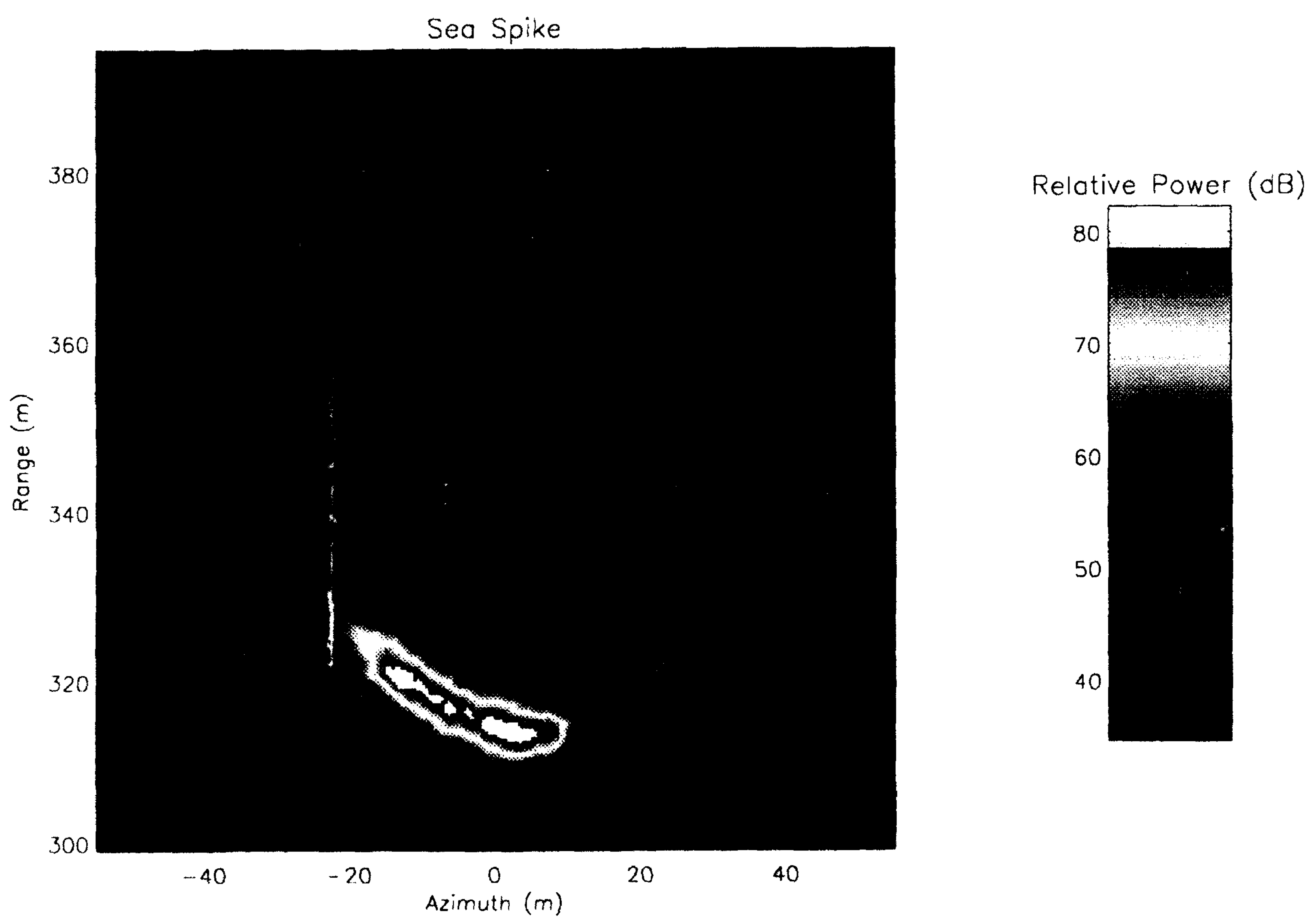

Figure 9: Backscattered intensity of ocean surface showing a "sea spike" due to enhanced scattering from a breaking wave.

6. Conclusion

The data presented in Chapter 5 clearly demonstrates that FOPAIR is capable of making fine-scale backscatter measurements of the ocean surface to ranges of several hundred meters. Sufficient dynamic range is present in these images (30-40 dB) to allow surface features such as breaking waves and non-breaking swells to be differentiated. The field of view of the array is sufficiently wide (20°) to provide cross track coverage of 105 m at a range of 300 m. Range coverage is 100 m using 64 range gates, and can be doubled if degraded azimuthal resolution can be tolerated. The antenna calibration has proven to be stable over periods of many days making frequent calibration unnecessary.

Following submission of this report Quadrant will turn FOPAIR over to the Microwave Remote Sensing Laboratory (MIRSL) of the University of Massachusetts. ONR is currently funding MIRSL to use FOPAIR during the upcoming Marine Boundary Layer Accelerated Research Initiative (MBL-ARI). MIRSL plans to bring FOPAIR to the Scripps Institute of Oceanography during July, 1993 where they will work together with Dr. Ken Melville studying breaking waves from the Scripps research pier. During this experiment, simultaneous measurements of breaking waves will be made from above and below the surface using FOPAIR and an imaging sonar system developed by researchers from Scripps. MIRSL researchers also plan to install FOPAIR on the Flip ship in early 1994 for a test run in preparation for the MBL-ARI Flip-based experiment in 1995.